# Settlement, Growth Rates and Depth Preference of the Shipworm *Bankia setacea* (Tryon) in Monterey Bay

BY

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(3 Plates; 6 Text figures)

## INTRODUCTION

For the past six years continuous studies have been in progress in Monterey Harbor and in the deeper water of Monterey Bay on fouling and boring organisms. The results of most of these investigations have been published (Miller, 1966; Mommsen, 1966; Haderlie 1968a, 1968b, 1969, 1970, 1971, 1972). Starting in June 1968 a series of separate studies was initiated whose aim was to make a detailed investigation of the settlement, growth rates and depth preferences of the shipworm *Bankia setacea* (Tryon, 1863). These studies continued until January 1972 and this paper presents not only the results of this latter 3½ year investigation but summarizes data on *Bankia setacea* from Monterey Bay collected earlier or already published.

The authors wish to acknowledge extensive help from various crew members of the Naval Postgraduate School's Hydrographic Research vessel for many hours of hard work at sea and the Department of Material Science and Chemistry of the Naval Postgraduate School for advice and use of radiographic and darkroom equipment. The Office of Naval Research (Foundation Program) and the Naval Oceanographic Office provided initial financial support for the project and the Naval Facilities Engineering Command has continued this support.

## AREA of STUDY

The principal focus of this study has been in the Monterey Harbor at a site under Municipal Wharf No. 2 (Figure 1). At this site wooden panels of a variety of sizes were continuously exposed to the marine environment for various times and at various depths for over five years from October 1966 to January 1972. In addition to douglas fir plywood panels and boards, blocks of Scotch pine and 4 × 4 inch fir timbers have also been exposed at various times during this period. The depth of water at this test site is approximately 23 feet at mean lower low water (MLLW) and the maximum spring tide range is about 9 feet. The Wharf is primarily supported by concrete piles spaced 8 to 10 feet apart, but has rows of creosoted douglas fir fender piles along each side. Some of these wooden piles have been in place for 25 years or more and many of them are severely bored by *Bankia setacea*, particularly near the mudline, and each year a few of these break off and must be replaced. All of the piles are covered with a luxurious fouling growth of acorn barnacles, anemones, mussels, ectoprocts, tunicates and polychaetes.

In addition to the harbor site, wooden panels designed to collect *Bankia* have been exposed in open water of Monterey Bay at depths of 50 feet off Del Monte Beach, at 100 feet depth off Del Monte Beach and off Fort Ord, and at 200 feet depth near "B" buoy off the Fort Ord Firing Range (Figure 1).

Sea surface bucket thermometer temperatures were taken daily in the harbor throughout the six year period of this study. These detailed temperature records are on file at the Naval Postgraduate School. Monthly temperatures are summarized from 1966 through 1971 in Figure 2. The monthly range of temperatures from minimum to maximum is represented by vertical bars. All daily sea surface temperatures for each month were averaged, plotted and connected by straight lines to represent average yearly temperature curves. The largest monthly temperature range of 11.3° to 16.8°C occurred in May 1967. The highest temperature (17.4°C) was recorded in September 1968, the lowest (9.5°C) in March 1971. The average temperatures indicate a general upward trend from January to September, with a sharp decline from September through December. Since the temperatures represented in Figure 2 are of the surface water in the harbor, they depict the highest temperatures and largest ranges in temperature to which harbor panels were exposed. Temperatures for January to June 1970 and July 1970 to January 1972 (see Figure 2) represent precise exposure temperatures for floating panels in the harbor. In the early phases of the project surface salinity in the harbor was determined weekly using a hydrometer. During the latter part of this study we relied on surface salinities for the southern part of Monterey Bay as determined by Hopkins Marine Station as part of the CalCOFI program (see Hopkins Marine Station, 1966–1971). Throughout this investigation surface salinities (when averaged monthly) ranged from 32.8‰ to 33.8‰.

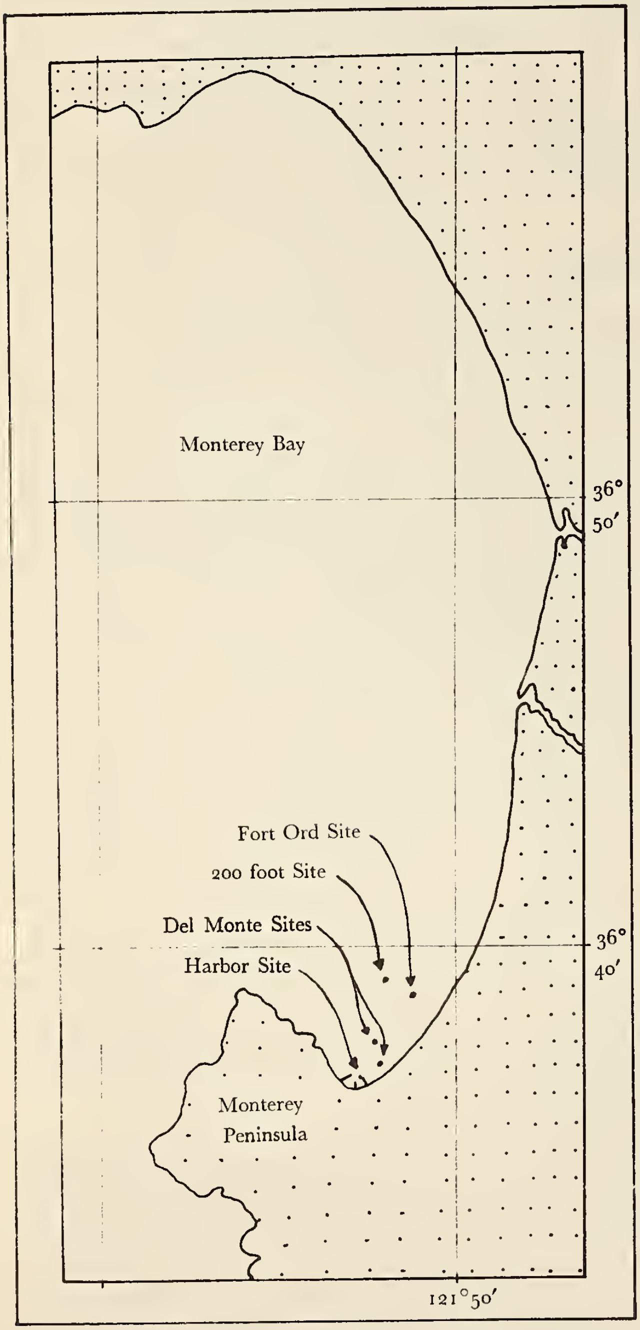


Figure 1

Map of Monterey Bay
showing sites of experimental panels

## MATERIALS AND METHODS

In the Monterey Harbor test site 8 × 10 × ¼ inch douglas fir plywood panels have been exposed continuously since October 1966. These panels were supported vertically in stainless steel racks; panels were spaced 3 inches apart. The racks were suspended from the wharf at various depths from the mid-intertidal to near the bottom at approximately 23 feet depth. Other racks were placed on floats at the water's surface. These panels were exposed foı varying periods of time throughout the period of study (Haderlie, 1968a, 1969, 1970). The plywood panels were primarily employed in the harbor to collect fouling organisms. However, they also collected borers (both *Bankia setacea* and the gribble *Limnoria quadripunctata* Holthuis, 1949) and although ¼ inch panels proved unsuitable for determining growth rates and maximum size of *Bankia* they none-the-less were useful in determining periods of settlement, for every two weeks at first and then monthly throughout the 5 year period panels were recovered and carefully analyzed with a binocular stereoscopic microscope (7× to 30× magnification). This made it possible to detect newly settled *Bankia* and to follow periods of settlement throughout the year at various depths. In the later stages of this project ¾ inch thick boards and 4 × 4 inch timbers of douglas fir were exposed simultaneously with the plywood panels and these surfaces collected far greater numbers of *Bankia* per settlement period. This indicated that ¼ inch plywood is not a suitable collector of shipworms and does not give a true indication of numbers of larvae present.

In the open water of Monterey Bay at depths of 50, 100 and 200 feet douglas fir boards 6 × 12 × ¾ inches were employed to collect borers. These are standardized panels being used by the Naval Oceanographic Office for long-

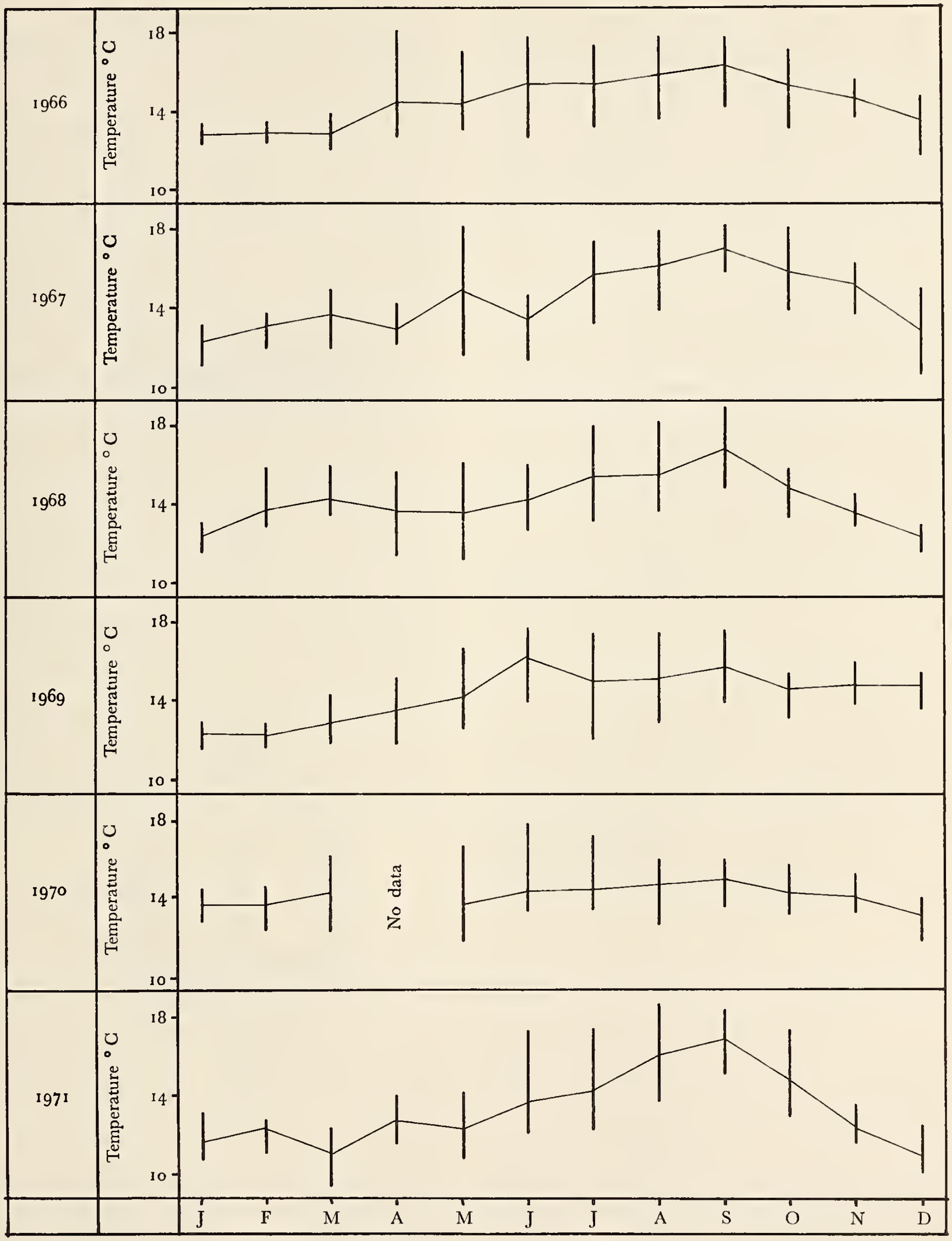


Figure 2

Summary of Surface Water Temperature in Monterey Harbor
from 1966 through 1971
Vertical bars indicate monthly range of temperature; connecting
lines indicate monthly average temperature

term studies of boring and fouling organisms in coastal waters of the world (DePalma, 1966). During the present studies these panels were arrayed on a taut line mooring system with an anchor on the bottom and floats on the surface. Each panel was attached at one end to the mooring line and was held vertically in the water near the bottom, yet was free to rotate and like flags could align itself with the prevailing currents (Haderlie, 1968b, 1971, 1972). Each month some panels were recovered and new ones exposed; others were allowed to remain in place for cumulatively longer periods of time up to one year. When returned to the laboratory these panels were analyzed with a microscope to detect newly settled borers. Panels harboring mature *Bankia* were either split open or x-rayed to determine number and size of the shipworms (see details of laboratory analyses below).

All of the studies so far described were primarily devoted to fouling organisms with only secondary attention given to borers. It was early realized that different techniques would have to be used in order to gather reliable data on growth rates and depth preferences.

Starting in June 1968 and continuing for 3½ years until January 1972 a series of boards, test blocks and timbers were exposed in the harbor area specifically for the purpose of collecting *Bankia setacea* and analyzing growth rates of shipworms at different depths and seasons. Settlement and growth of foulers was also monitored on most of these test surfaces but the fouling studies were incidental to the main effort devoted to the shipworms. As different test materials of varying sizes were used during the course of this study, it seems best to describe materials and methods used under 5 different headings, for there was this number of different techniques used. Several of these different series were overlapping in time or ran concurrently with one another as will be seen.

## O. E. C. D. Project

From 1 June 1968 to 1 June 1969 we participated in a research program sponsored by the Committee for Research Co-operation on the Preservation of Wood in the Marine Environment. This Committee is part of the Organization for Economic Co-operation and Development (O.E.C.D.). The studies made in Monterey were part of a world-wide program whose objectives were to simultaneously study boring organisms, fouling and fungi that degrade wood in the marine environment. Similar test materials and techniques were used at a great number of coastal stations around the world. The only aspect of this year-long study to be reported here will be in connection with *Bankia setacea* settlement and boring into the test blocks.

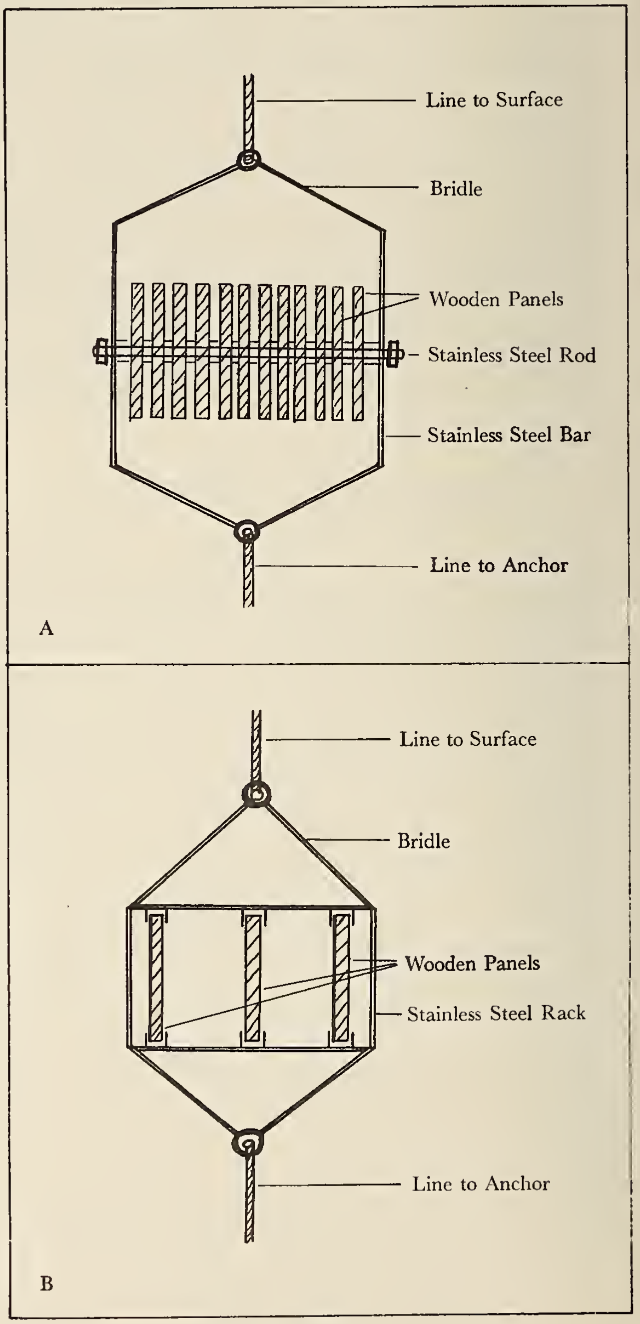


Figure 3

Sketch Illustrating Panel Arrays as Exposed in Monterey Harbor
A. Array used in *Bankia* Series I
B. Array used in *Bankia* Series II

The materials used in this part of the investigation were test blocks of flat sawn sapwood of Scotch pine (*Pinus sylvestris* Linnaeus). Two different-sized blocks were used: small blocks measuring 10 × 20 × 2cm and large blocks measuring 10 × 10 × 50cm. In each test block a hole was drilled at either end and lined with plastic tubing. A polypropylene line 18 inches long ran from the bottom hole to a small anchor weight that rested on the bottom in approximately 23 feet of water. From the upper hole in the test block a line ran up to the surface where it was secured to the wharf. Two of the small test blocks were installed on the first of each month throughout the year; one of these was recovered at the end of one month, the other remained exposed for two months before recovery. After removal from the water the small blocks were taken to the laboratory for analysis. After examining each block microscopically for foulers and borers the blocks were split to check for number and size of *Bankia setacea* present. Four large test blocks were exposed at the same position as the small ones, but remained in the water for longer periods of time. After being placed in the water on 1 June 1968 two of these large test blocks were removed after six months on 1 December 1968; the remaining two remained exposed for one year and were recovered on 1 June 1969. After recovery these large test blocks were analyzed by cutting three sections from each block at points corresponding to ¼, ½ and ¾ of the block length. The diameter and number of bore holes were recorded and, using a piece of graph paper to trace the outline of the remaining wood, an attempt was made to calculate the percentage of wood destroyed at each level. The results of these studies will be presented below.

## *Bankia* Series I

In order to continue this specific investigation on *Bankia setacea* after the O.E.C.D. project was terminated a new series of panels consisting of 6 × 12 × ¾ inch flat sawn douglas fir (*Pseudotsuga douglasi* Carr) panels were exposed. This group of panels is referred to here as Bankia Series I and was followed, using slightly different techniques in the way the panels were arrayed, by Series II and Series III to be described below.

The Series I panels were arrayed as shown in Figure 3A. Twelve panels, each with a ½ inch hole drilled in the center, were strung on a stainless steel rod with a 1 inch plastic tubing spacer between each 2 panels. A stainless steel bar 18 inches long was secured by wing nuts to the ends of the rod and two bridles of ½ inch polypropylene line were secured at the ends of each bar. To the bottom bridle a 50 lb. concrete anchor was secured; with this anchor resting on the bottom in about 23 feet of water the center of each panel was about 2 feet above bottom. From the top bridle a line extended to the surface and was secured to the wharf. To make certain the entire bridle would remain taut and the panels kept above the bottom even after they became waterlogged and heavy with fouling growth a 5 × 9 inch plastic toggle float was placed on the recovery line just above the upper bridle. The panels were thus held vertically but were free to rotate end over end on the rod.

An array of 12 panels was initially exposed on 1 May 1969. On 1 June 1969 the array was lifted and one panel removed for analysis; a new so-called monthly panel was placed on the rod and the array submerged. On the first of each succeeding month two panels were removed; one was the monthly panel exposed for one month only, the other was a cumulative panel exposed for two months or more up to one year. In the laboratory each recovered panel was examined microscopically for newly settled *Bankia;* the panel was then split longitudinally by sawing with a band saw giving two panels approximately ¼ inch thick. The extent of *Bankia* damage and size of individual shipworms could then be determined.

## *Bankia* Series II

Throughout the investigations so far described it was realized that a better technique for studying *Bankia* growth rates would be one where individual shipworms could be measured periodically without destroying or harming the animals or the panels in which they were living. We therefore deployed a new series of panels with the specific objective of following growth rates by radiographic means.

Attwood & Johnson (1924) were the first to publish an X-ray photograph of shipworm infested wood and many investigators since have used X-ray to estimate the intensity of wood infestation with marine borers. In studying the growth rates of *Teredo* Crisp, Jones & Watson (1953) used stereoscopic X-ray to follow growth rates and site of attack. Following each examination, the infested panels were returned to the water to permit continued development. Lane (1959) used a series of spaced X-ray examinations of *Teredo*-infested wood to determine size and average length of life of the shipworms. *Bankia* has been investigated using radiographic techniques of Ralph & Hurley (1952), Trussel, Greer & LeBrasseur (1956), Taylor (1956) and Quayle (1956, 1959).

In Monterey Harbor a group of panels referred to as Series II were exposed from 1 January 1970 to 1 July 1970 and another group called Series III were exposed from 1

July 1970 to 1 January 1972, with a few remaining exposed until 1 May 1972 when the project was terminated. Representatives of these panels were subjected to monthly X-ray examination and the analysis of these radiographs has given us considerable data on the growth rates and intensity of infestation of *Bankia* in the harbor.

Series II panels consisted of 5 × 13 × ¾ inch douglas fir boards which were placed in stainless steel racks that held the panels vertically with the edges parallel to the water surface. Three panels spaced 3 inches apart were arranged in the racks as shown in Figure 3B. A bridle on the bottom of the rack was connected to a line leading to an anchor weight that rested on the bottom. From an upper bridle a line extended to the surface and was secured to the wharf. A total of four racks each containing three panels was exposed at different depths. One rack, termed Shallow Rack, was positioned 1 foot below the lowest tide (3 feet below mean lower low water), a second Midwater Rack was positioned 10 feet below low tide (13 feet below MLLW) and a third called the Deep Rack was placed 20 feet below the lowest tide (23 feet below MLLW) and just above the bottom. A fourth rack was provided with a system of floats that kept the upper edges of the three panels at the water line. This Floating Rack was secured to the wharf by a series of pulleys and counterweights so that it continually floated at the surface regardless of tides or currents. The objectives in having racks at different depths was to determine depth preference of *Bankia* in the harbor and settlement time and growth rates at different depths.

All of these Series II panels remained in the water for six months except for the brief periods when some of them were removed for analysis. On the first of each month following initial exposure each of the four racks was recovered. From each rack Panel #2 and Panel #3 were removed. Panel #1 (control panel) remained in place in the rack and was immediately replaced in the water. The two remaining panels were taken to the laboratory. Panel #2 was treated exactly like Panel #3 except that only Panel #3 was X-rayed while Panel #2 was being examined for fouling organisms. The basic idea in having essentially two control panels was to see if removal from the water for short periods monthly had any influence on growth rates and especially to see if the radiation from the X-ray was harming (or stimulating) the living *Bankia*. When not being X-rayed all panels removed from the racks were kept in an aquarium with running sea water. Within an average of 2 hours the panels were returned to their racks in the harbor.

In the early phases of the study using X-ray analysis it was found that the external calcareous fouling growth often confused the resulting radiograph. To avoid this problem, panels used in the Series III study (to be discussed below) had the fouling growth removed from the panels by stripping off a plastic envelope that had been placed around the girth of the panel. In order to avoid injuring the siphons or pallets of living *Bankia* the fouling growth was not removed from the exposed ends of the panels. Panels to be X-rayed were labeled with distinctive designators composed of radio-opaque letters and numbers that provided a permanent legend on each radiograph. Each panel was then placed in a polyethylene bag and two such labeled panels were placed with the panel faces in contact with a sheet of Kodak NS-2T (no-screen medical) X-ray film measuring 11 × 14 inches. A Norelco Searchray, Type 1206, X-ray machine was used to expose the panels and film. Each set was exposed for 5 seconds with power of 30 Kv at 5 milliamperes. A plate of 1/16 inch aluminum was placed between the X-ray tube and panels to reduce short wave radiation. Examples of the resulting radiographs are shown in Figures *6–14* and *16–18*.

## *Bankia* Series III

Toward the end of the six-month study on the Series II panels it was realized that it was very difficult to follow the growth of individual shipworms for some of the panels were so heavily infested and the tubes so intertwined that individual burrows could not be followed. The borers had initially entered the wood on all of the exposed surfaces and led to a confusing series of burrows. In addition many of the panels, especially the deeper ones, were so heavily infested and the shipworms so crowded that none of them could achieve maximum size due to space limitation (see Figure *16*). Calcareous fouling organisms encrusting the surface of the panels also added complexity to the interpretation of the radiographic pictures. A new series of panels was therefore deployed in an attempt to correct these deficiencies and to collect additional data.

Series III panels were first exposed on 1 July 1970 and all of them remained in the water for 18 months until 1 January 1972. Most of the panels were then removed, X-rayed, and sectioned but a few panels were left in place for an additional 4 months until 1 May 1972 to determine longevity and to gain additional data.

The panels in Series III were deployed in racks similar to the previous study (Series II described above) except that racks designed to hold four panels each instead of three were used. Three of the panels were treated as has been described above for the Series II group. The fourth panel was an additional control. At the time of lifting the racks each month this fourth panel was removed and merely allowed to remain in air in a protected area of the wharf until the panels removed to the laboratory were returned and then all panels were replaced in racks and replanted.

The position of the racks was exactly the same as in Series II except that one more rack was used. This additional rack of four panels was suspended from the Floating Rack and was positioned two feet below the water's surface. This rack moved up and down with the tide but remained submerged. To distinguish it and its panels from the Floating Rack it was designated Floating Submerged Rack. Three out of the four Series III panels were partially enclosed in a plastic envelope to prevent *Bankia* penetration except on the ends of the panels.

The panels were all exposed for 10 days until they became water-soaked. Then panels number 1, 2 and 3 were removed and wrapped snugly with wide Scotch #490 (Seran) tape. This tape covered all parts of the panel except the two ends. The tape did not stick to the wet wood but formed a tight impervious envelope for each panel. *Bankia* could enter the wood only from the exposed ends of the panels. Shipworms that may have entered other surfaces of the panel during the initial soaking period soon died due to being cut off from the water. The idea here was to limit the number of *Bankia* entering any one panel so that their growth could be more easily monitored and to provide each shipworm with enough space to achieve its full growth potential. The fouling growth which can easily confuse the interpretation of the radiographic pictures was removed prior to X-raying by removal of the plastic tape. Panel No. 4 in each rack was not covered with Seran but remained exposed on all surfaces. This panel from each rack was taken to the laboratory each month and examined for foulers but was not subjected to monthly X-ray. On 1 July 1971 after 12 months exposure it was finally removed permanently, X-rayed and sectioned for study. Routine monthly X-ray examination of Panel No. 3 in each rack continued for 18 months until 1 January 1972.

### Experimental Piles

In addition to these panel studies in the harbor area a series of large timbers was also used. The earlier O.E.C.D. investigation had shown that blocks approximately $4 \times 4$ inches in cross section were excellent collectors of shipworms. To study the entire vertical range of *Bankia* attack in the harbor a series of experimental piles was used. These consisted of $4 \times 4$ inch planed clear douglas fir timbers 18 to 20 feet long. The two timbers were secured together with about a 3 foot overlap using stainless steel straps. This produced one long "pile" over 30 feet long. One end of the pile was placed in a pointed stainless steel cap filled with lead. The pile was then driven into the bottom so that the lower 6 inches of the pile was below midline. The pile stood vertically in the water and was long enough so that about the upper 10 feet extended above the waterline at 0 tide level. The experimental pile was secured at two points to strong cross timbers running between the regular supporting piles of the wharf. These experimental piles gave complete coverage of the water column from above the high tide level to below mudline level in water 23 feet deep at MLLW. Not only did these timbers allow investigation of *Bankia* penetration at all levels in the harbor but produced valuable data on the vertical distribution of fouling organisms throughout the same distance. These data on foulers will be published at a later date.

A total of four experimental piles were employed from 1 January 1970 to 1 January 1972. Each pile remained in the water for a 6-month period, either from January through June or from July through December of each year. At the end of each 6-month period a pile was removed and replaced by a new one. After removal the experimental pile was taken to the laboratory where it was carefully analyzed for foulers and was photographed section by section. After a period of drying the pile was cut into 6-inch sections from the area that was at the mudline to the area where the uppermost barnacles grew indicating high waterline. Each of these sections was then analyzed for number of *Bankia* bores, diameter of bore holes and percent destruction of the timber at that level.

## PERIODS OF SETTLEMENT

In pioneering studies on shipworms of the Pacific coast Miller (1926) and Kofoid & Miller (1927) reported that *Bankia setacea* in San Francisco Bay has a breeding season and settlement beginning in February and ending in the early summer with a peak in April or May. Johnson & Miller (1935) found the principal season of settlement of *B. setacea* in the Friday Harbor area of Washington was during the months of October, November and December with little or no settlement in January and February. Settlement began again in March or April and continued sporadically during the summer until an acceleration to full peak was achieved in October. These authors concluded that a water temperature of from 7° to 12°C was the limit for breeding in Puget Sound. In southern California Coe (1941) found that breeding in *Bankia* occurred in the fall and spring with no spawning in summer or winter. In various places in British Columbia Neave (1943), Black & Elsey (1948), Brown (1955), Trussel, Greer & LeBrasseur (1956) and Quayle (1959) reported settlement of *Bankia setacea* at different times throughout the year. The main period seemed to be in the fall months but in many places breeding occurred throughout the year. Most of the above studies were of fairly short-term duration and QUAYLE (*op. cit.*) pointed out the need for continuous long-term observations.

Figure 4 presents data on the settlement of *Bankia setacea* in Monterey Bay for a period of five years from October 1966 to September 1971. Data are given for the four primary study sites at 20, 50, 100 and 200 feet depths. Essentially continuous observations were made in the

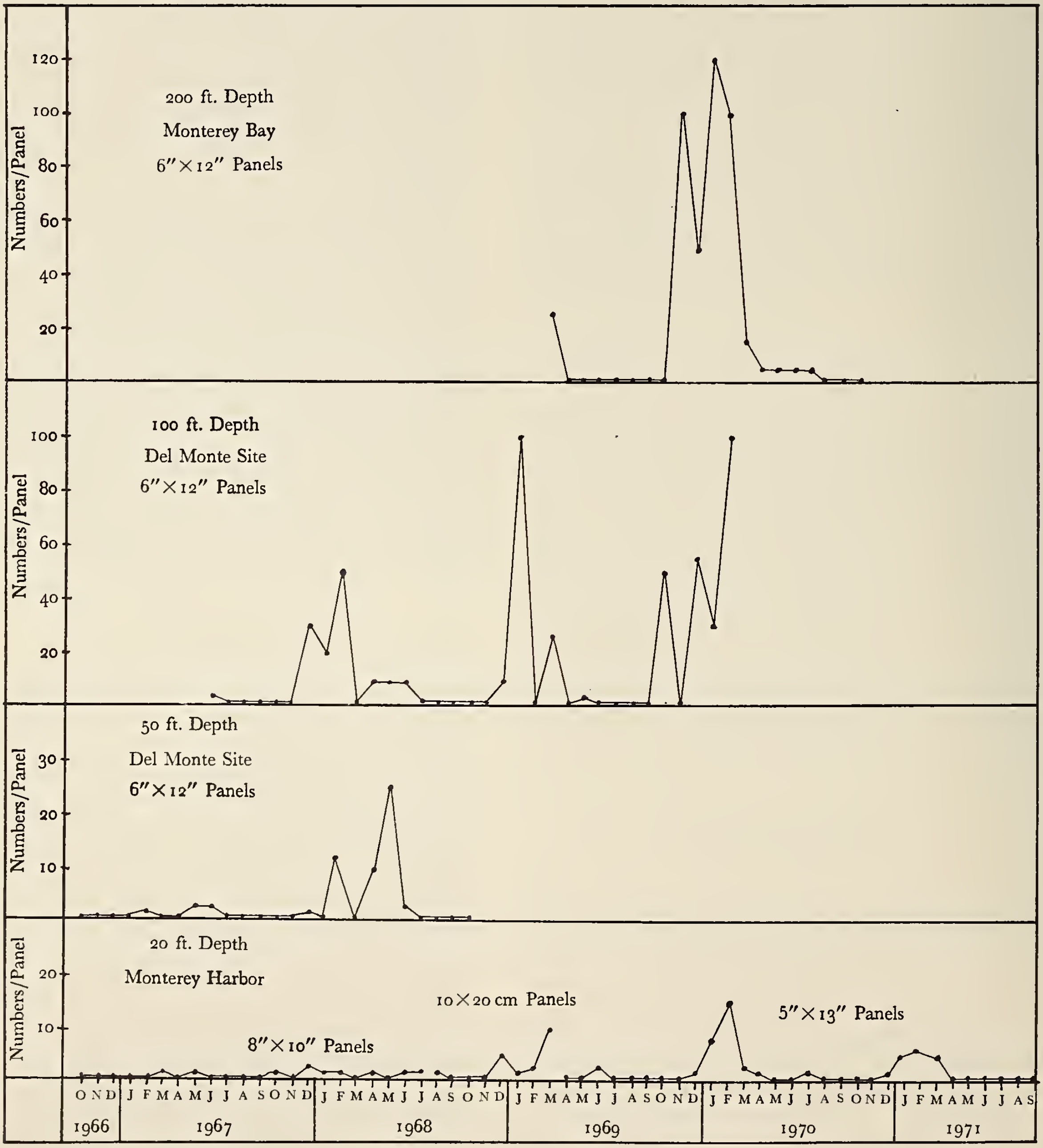


Figure 4

Numbers and Time of Settlement of *Bankia setacea* in Monterey Bay harbor area at depths of 20 feet for the entire five year period. In the deeper water the investigations were for shorter periods of from one and one half to nearly three years.

As has been mentioned above, standardized $6 \times 12 \times \frac{3}{4}$ inch douglas fir panels were used continuously in the studies outside the harbor and were used (in slightly different dimensions) in the harbor during the last half of the project. Plywood and small Scotch pine test blocks were used during the initial half of the study in the harbor. The data in Figure 4 came only from panels that were in the water for a one month period, thus all of the shipworms counted settled during the month of exposure. In all cases, the flat surfaces of the panels were the only surfaces scanned microscopically to establish the counts, and many of our X-rays show that the majority of the shipworms entered the ends or the edges of the panels. The data given in Figure 4 therefore represent minimum counts per panel and are not an absolutely accurate representation either of settlement time or intensity. As all the panels were exposed for the same or overlapping periods, Figure 4 does make it possible to compare relative intensities of settlement and season at various depths in Monterey Bay.

As Figure 4 shows, the maximum number of shipworms settling on any one panel was directly correlated with water depth, the greatest intensity of settlement was at 200 feet depth, the least at 20 feet depth in the harbor. This finding is rather surprising for one would expect more larvae to be available for settlement in the harbor where there are many infested wooden piles and wooden hulled boats to serve as sources of shipworm larvae. The source of the larvae in deeper water is unknown, but benthic studies carried out in Monterey Bay for many years indicate that wood is not commonly found lying on the bottom and driftwood is not often seen. Other investigators (e.g., Coe, 1941; Quayle, 1953) have reported that the planktotrophic larvae of *Bankia setacea* have a long pelagic life and may have a swimming period of 4 weeks. The larvae penetrating panels in the deeper stations of this study may therefore have come from some distance away although the wooden structures in Monterey Harbor are the nearest source.

As indicated in Figure 4 the number of shipworms settling on any one monthly panel in the harbor, regardless of panel size or kind of wood, was quite low. The periods of maximum settlement in the harbor were March 1969 (45/sq. ft.), February 1970 (30/sq. ft.) and February 1971 (18/sq. ft.). In general, throughout the period, late summer and early fall were periods of minimal or no settlement in the harbor.

At depths of 50 feet in the open water of Monterey Bay (off Del Monte Beach approximately 1200m from the harbor) shipworm settlement for a two year period was monitored (Haderlie, 1968b). Figure 4 presents the data from this study and shows that during late 1966 and throughout 1967 there were few *Bankia* settling but two peaks were recorded in 1968. In February there was a settlement of 24/sq. ft. and in May a settlement of 50/sq. ft.

Data from nearly three years of observations on shipworm settlement at 100 feet depth in Monterey Bay are also presented in Figure 4 (Haderlie, 1971). October through July appears to be the season of settlement at 100 feet depth. Peak settlement again occurred during the winter months: 90/sq. ft. in February 1968, 200/sq. ft. in January 1969 and 200/sq. ft. in February 1970. In late summer and early fall there was little or no settlement.

About 1½ year's data on *Bankia* settlement at 200 feet depth have been collected in Monterey Bay (Haderlie, 1972). The season of settlement appears to be the same as at shallow depths in the open water with maxima between November and March. A peak settlement of 240/sq. ft. of panel surface was recorded in January 1970. This is the most intense rate of settlement recorded so far in our studies in Monterey Bay. No settlement occurred between April and October 1969 but in the following year a few shipworms settled throughout the spring and summer up to August.

To summarize, data from various depths in Monterey Bay indicate that in general the settlement season of *Bankia setacea* is from late fall to early summer with a maximum settlement in most areas during the winter months and a minimum in late summer and early fall. The intensity of settlement increases with depth to 200 feet.

Other investigators studying *Bankia setacea* settlement in shallow water along the California coast have concluded that *Bankia* spawns and settles in the shallow water when water temperatures are at a minimum (Miller, 1926; Kofoid & Miller, 1927). This seems to be true also in the Monterey Harbor where minimum surface temperatures of about 11.5°C are recorded in the winter and spring months (Skogsberg, 1936; Haderlie, 1968a). Due to the influence of upwelling, however, in the open water of Monterey Bay at depths of from 10 to 100m the minimum temperatures are found during May, June and July. At 50m depth, for example, temperatures averaging 8.0°C are found in May and June, whereas the warmest temperatures of the year at this depth (approximately 11.0°C) are found during December and January (Skogsberg, 1936). Thus in the open water of Monterey Bay at depths

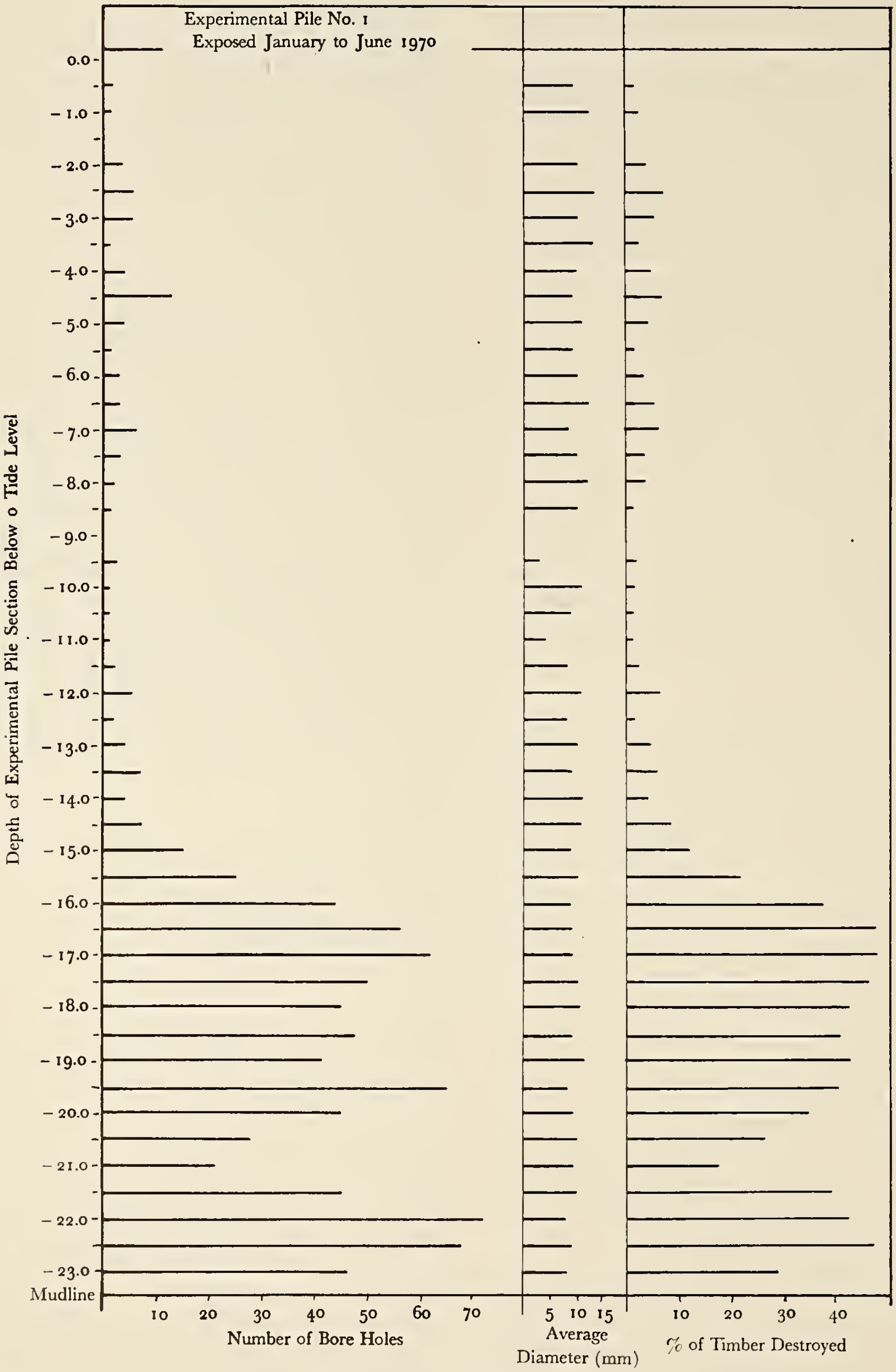


Figure 5

Number of *Bankia* Bore Holes, Average Diameter of Holes and Percent of Timber Destruction at Various Levels on Experimental Piles Exposed in Monterey Harbor

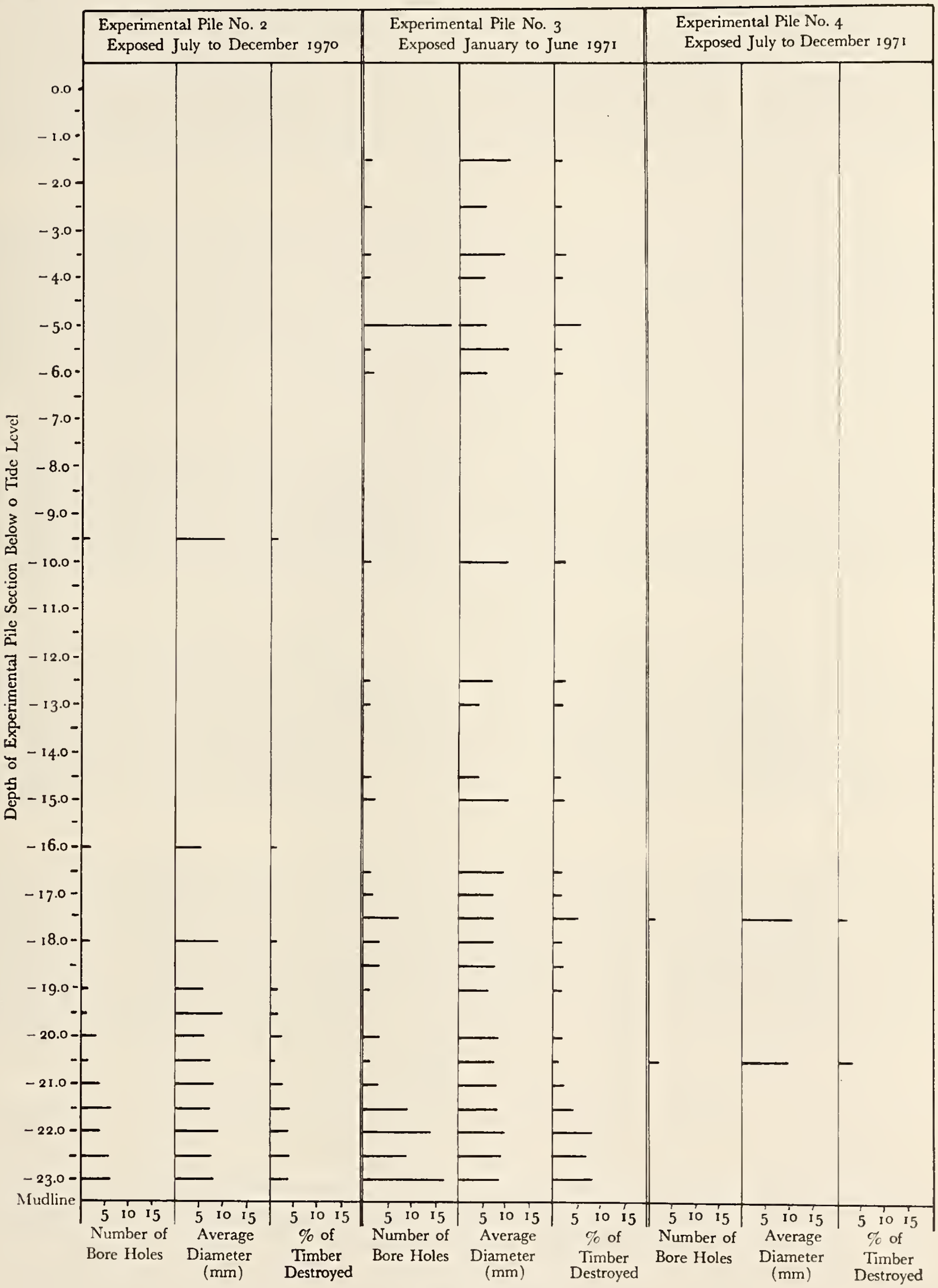


Figure 5 [continued]

Number of *Bankia* Bore Holes, Average Diameter of Holes and Percent of Timber Destruction at Various Levels on Experimental Piles Exposed in Monterey Harbor where these investigations were carried out *Bankia* settles following periods of maximum temperature in late fall and winter and may be inhibited following periods of minimum temperature in late summer and early fall.

## DEPTH PREFERENCE

As has been discussed above, the intensity of *Bankia* settlement in Monterey Bay seems to increase with depth at least to 200 feet. And on panels exposed for long periods of time in the open water of the Bay it has been found that total destruction of untreated wooden panels occurs at all depths studied after about 7 months exposure provided initial exposure occurred during a period when *Bankia* was settling. In the harbor water, panels last for a longer period of time and may still be relatively intact after 12 months exposure.

It has been long known that *Bankia* tends to concentrate its attack near the mudline on pilings whereas a few feet above the mudline the wood may be relatively free of the borers (Kofoid & Miller, 1927). Panels suspended at various depths in Monterey Harbor are attacked throughout the water column, with greater settlement and destruction in the deeper positions. In none of our previous studies, however, did we have experimental wood exposed at all levels from below mudline to above the surface.

Starting on 1 January 1970 and continuing to 1 January 1972 four "experimental piles" were each exposed consecutively for six month periods. As explained above, the $4 \times 4$ inch douglas fir timbers were driven into the substrate and extended up vertically to above waterline. After a six month period these timbers were removed and sectioned at 6 inch intervals to determine number of bore holes, size of each, and the amount of timber destruction at each level. Data from the analysis of sections of these experimental piles are presented in Figure 5.

As discussed earlier, considerable variation occurs from year to year in the number of shipworm larvae settling on panels. The same was found to be true on the experimental piles as is obvious from the findings summarized in Figure 5. The first pile exposed (from January to June 1970) attracted the greatest number of *Bankia* and suffered the greatest amount of destruction. Some larvae settled on and bored into the wood at nearly all levels from the low intertidal to the mudline with the greatest attack on the pile within seven feet of the bottom. The maximum number of bore holes in the pile was found in a section cut one foot above mudline where 72 bore holes averaging about 8 mm in diameter were measured and these resulted in approximately 42% of the wood being destroyed at this level. Slightly fewer bore holes (68) were found 6 inches above mudline but because these averaged about 9 mm in diameter the total destruction of wood at this level was about 47%. The data from Pile #1 also indicates that the average size of the *Bankia* bores was remarkably uniform in diameter regardless of the level in the water column and regardless of the total number of shipworms infesting the wood. We cannot comment on the comparison of the length of the shipworms for in these pile studies we were not measuring length of burrows. In relatively thin panels it has been found that great numbers of *Bankia* in a single panel lead to crowding and limit the size of each bore hole. In this case of the experimental piles, however, the $4 \times 4$ inch cross sectional area was such that 70 or more shipworms forming burrows up to 10 mm in diameter could occur without excess crowding and stunting of growth.

Experimental Pile #3 (see Figure 5) was exposed during the same time interval in exactly the same spot but a year later (from January through June 1971). As can be seen, the pile was attacked from very low in the intertidal zone to the mudline, but not at all levels, and the number of shipworms settling was quite low compared to those settling in Pile #1 a year earlier. Panels exposed in the immediate vicinity of the experimental piles for the purpose of detecting settlement time showed that fewer *Bankia* settled in the first half of 1971 than in the comparable period in 1970. Again in this pile the major area of settlement was within 7 feet of the bottom. The maximum number of bores in this zone was at the mudline (total of 17). The curious anomaly seen in Figure 5, Experimental Pile #3, where a heavy settlement is indicated at –5.0 feet can be explained as follows: As described above, two $4 \times 4$ inch timbers were secured together in order to get a pile of sufficient length to extend from the bottom to above the water line. The lowest of

### Explanation of Figures *6* to *11*

Consecutive monthly X-ray photographs (1 May 1971 to 1 January 1972) of a single *Bankia* specimen in a $5 \times 13 \times \frac{3}{4}$ inch douglas fir panel exposed floating just below the sea surface in Monterey Harbor

Figure *6*: *Bankia* specimen in burrow 48 mm long one month after initial detection

Figure *7*: Second month burrow; 116 mm in length

Figure *8*: Third month burrow; 211 mm in length

Figure *9*: Fourth month burrow; 279 mm in length

Figure *10*: Fifth month burrow; 363 mm in length

Figure *11*: Sixth month burrow; 437 mm in length

Figure *6*

Figure *7*

Figure *8*

Figure *9*

Figure *10*

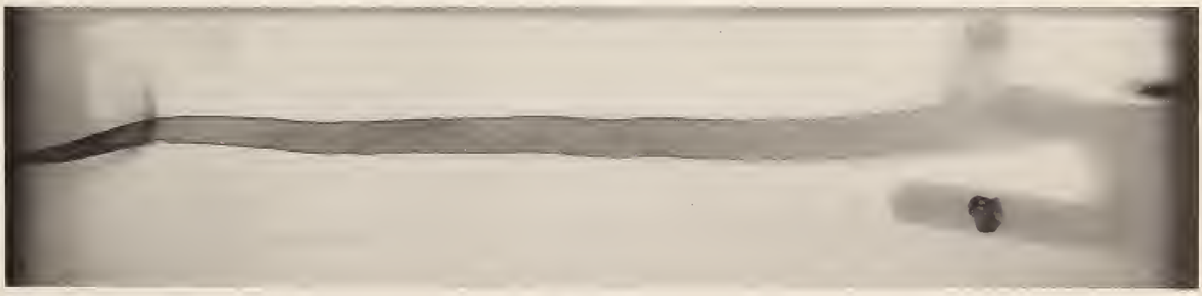

Figure *11*

these two timbers extended up to just a few inches above the –5.0 ft. level. The exposed end grain of this timber apparently served as an attractive point of entrance for several shipworms which were detected when the timber was sectioned at the –5.0 ft. level just below this end.

Figure 5 also indicates that during the period July through December *Bankia* settlement was somewhat different from the first half of the year. In both Experimental Piles #2 and #4 exposed during the latter half of each year the number of shipworms settling was considerably smaller than earlier; they settled only in the lower half of the water column. During July 1970 there were *Bankia* larvae settling in the harbor, but no others settled until December (see Figure 4). Thus the shipworms detected in Experimental Pile #2 (that was removed for examination the last of December 1970) presumably settled in July and most of the burrows were of fairly uniform size. In 1971, however, there was no *Bankia* settlement detected in the harbor from April through September. Experimental Pile #4 carried only three *Bankia,* one at the –17.5 ft. level and two at the –20.5 ft. level. All of these were of average maximum diameter, so it is assumed that these settled in October to have grown to the size they attained by late December.

The above data show that considerable variation occurs from year to year. In the O.E.C.D. project described earlier and carried out in 1968 and 1969 a series of Scotch pine test blocks of approximately the same cross sectional area as the experimental douglas fir piles were suspended 2 feet above the bottom and it is interesting to compare the results of this investigation with the data presented in Figure 5. Table 1 presents the data from test blocks of the O.E.C.D. series that measured $10 \times 10 \times 50$ cm in which *Bankia* penetrated. Only Test Blocks #1a and #1b of the O.E.C.D. series are comparable to the experimental piles, for they were in the water for a six month period. Test Blocks #2a and #2b were exposed for 12 months and therefore show not only considerably more shipworm bores but also a much higher percentage of wood destruction. In both June and July 1968 (during the initial period of O.E.C.D. test block exposure) *Bankia* larvae were settling in the harbor (see Figure 4). Table 1 shows that by the first of December 1968 these test blocks carried a total number of shipworms similar to what was found in sections of Experimental Pile #1 at comparable depths in June 1970.

## GROWTH RATES

Due to the fact that the animals are hidden in the substrate there are many difficulties involved in studying the growth rates of boring organisms. Periodic sectioning of experimental panels infested with shipworms of known age has been the usual technique used, but this destroys the organisms and makes additional growth observations impossible. It has been long recognized that radiographic techniques should make it possible to follow the growth of individuals or populations of borers for long periods of time not only to determine rates of growth at different seasons but ultimate longevity of individual borers. Quayle (1956, 1959) was one of the first to use such techniques in the study of *Bankia setacea* and has reviewed the literature up to 1959.

The first growth studies in California on *Bankia* were conducted by Kofoid & Miller (1927). They determined growth rates in San Francisco Bay by measuring the size of bore holes in test blocks of known age and reported average rates of growth of from 23 mm per month for specimens 6 weeks old to 63 mm per month for an in-

Table 1

*Bankia setacea* bores, average diameter of bore holes and percent of Scotch pine blocks destroyed at different levels in 10 cm × 10 cm × 50 cm test blocks

| Test block number | Period of exposure | Sectioned $\frac{1}{4}$ from lower end | | | Sectioned $\frac{1}{2}$ from lower end | | | Sectioned $\frac{3}{4}$ from lower end | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | No. of bores | Ave. diam. bore holes (mm) | % of wood destroyed | No. of bores | Ave. diam. bore holes (mm) | % of wood destroyed | No. of bores | Ave. diam. bore holes (mm) | % of wood destroyed |
| 1a | 1 June 1968 - 1 Dec. 1968 | 54 | 9.0 | 34 | 44 | 9.0 | 33 | 48 | 10.0 | 30 |
| 1b | 1 June 1968 - 1 Dec. 1968 | 68 | 8.0 | 43 | 35 | 10.0 | 22 | 35 | 10.0 | 22 |
| 2a | 1 June 1968 - 1 June 1969 | 100 | 10.0 | 79 | 83 | 10.0 | 65 | 88 | 8.0 | 44 |
| 2b | 1 June 1968 - 1 June 1969 | 140 | 8.0 | 80 | 105 | 10.0 | 82 | 110 | 8.0 | 75 |

Table 2

Series II (1 January 1970 to 1 July 1970) terminal panel data

| Panel Depth | Panel Number | Months of Growth | Total No. of *Bankia* | Maximum Length (mm) | Maximum Diameter (mm) | Average Growth for 3 Months (mm) / No. of Measurements | % Destruction | Average % Destruction at each Depth |
|---|---|---|---|---|---|---|---|---|
| Floating at Surface | 1 | 3 [1] | 3 | 53 | 7 | 53/1 | 1 | |
| | 2 | 3 [1] | 2 | 107 | 8 | 107/1 | 1 | 1 |
| | 3 | 1 | 1 | 7 | 2 | 0 | 0 | |
| 3 ft. below MLLW (Shallow) | 1 | 3 [1] | 40 | 360 | 9 | 138/25 | 21 | |
| | 2 | 3 [1] | 45 | 290 | 11 | 114/34 | 22 | 19 |
| | 3 | 3 | 47 | 247 | 9 | 118/34 | 14 | |
| 13 ft. below MLLW (Mid-Water) | 1 | 3 [1] | 30 | 296 | 7 | 126/26 | 23 | |
| | 2 | 3 [1] | 30 | 291 | 10 | 114/17 | 3 | 14 |
| | 3 | 3 | 48 | 298 | 9 | 160/32 | 17 | |
| 23 ft. below MLLW (Deep) | 1 | 3 [1] | 84 | 235 | 8 | too crowded | 26 | |
| | 2 | 3 [1] | 145 | 312 | 10 | too crowded | 24 | 28 |
| | 3 | 3 | 156 | 425 | 8 | too crowded | 34 | |

[1] assumed duration of growth

dividual 8 months old. At Friday Harbor, Washington, Johnson & Miller (1935) using similar techniques found the burrows of *Bankia* increased in length at an average rate of 10 mm per month.

Quayle (1956, 1959) carried out an experiment involving 8 fir panels of about the same size employed in our studies in Monterey Bay. These panels were suspended 3 feet below the surface in water at Ladysmith, British Columbia. Panels were removed at monthly intervals and X-rayed. With water temperature below 10°C growth rates were low (50 mm per month) but at temperatures above 10°C a rate of 100 mm per month was the average. The most rapidly growing individual shipworm attained a length of 610 mm in 5 months or a rate of growth of 122 mm per month. Quayle found that the rate of increase in the diameter of the burrow was similar to that of length, and the greatest diameter attained was 12 mm.

In our studies in Monterey Harbor *Bankia setacea* growth rates and destruction of the wood substrate will be discussed in terms of numbers of organisms within a given area of wood surface (settlement), growth in length and diameter for specific periods of time, and percentage destruction of wood through loss in panel weight. Radiographic techniques have added precision and insight to the growth measurements. Repetitive monthly X-rays of

## Explanation of Figures *12* to *15*

Figure *12*: Seventh month burrow; 541 mm in length
Figure *13*: Eighth month burrow; 672 mm in length
Figure *14*: Ninth month burrow; 797 mm in length
Figure *15*: Standard photograph of split panel showing terminal burrow of shipworm shown in Figures 6 to 14

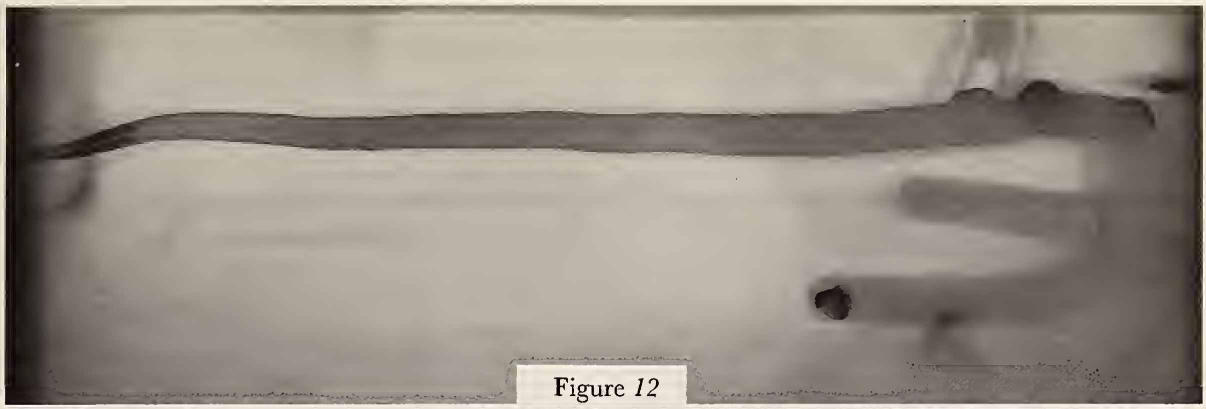

Figure *12*

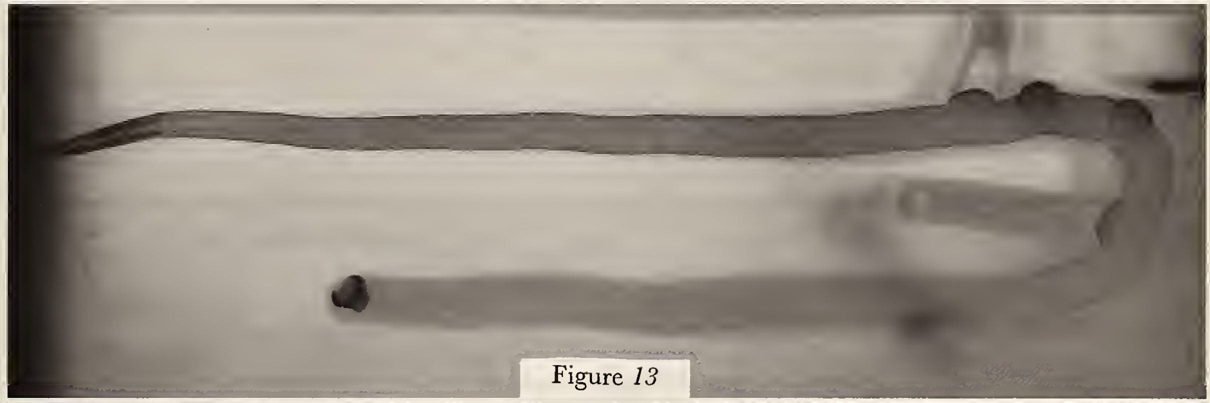

Figure *13*

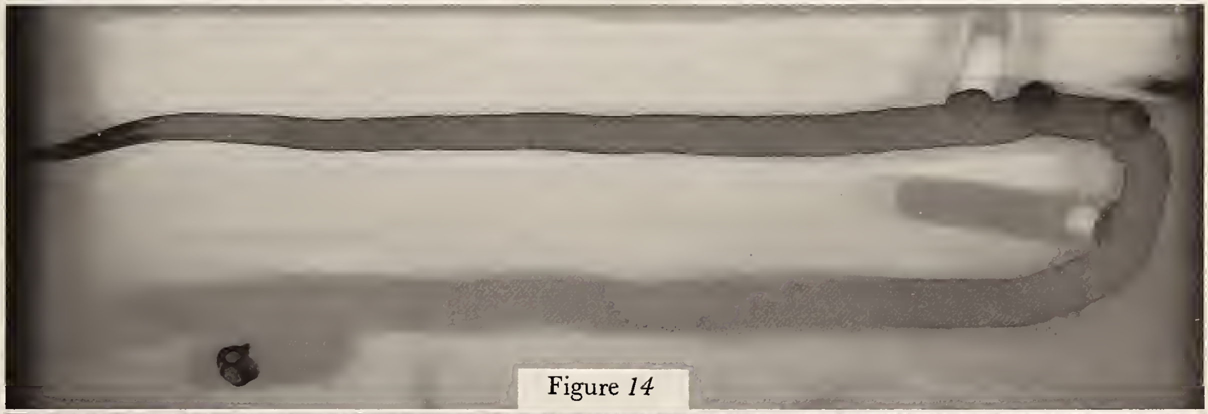

Figure *14*

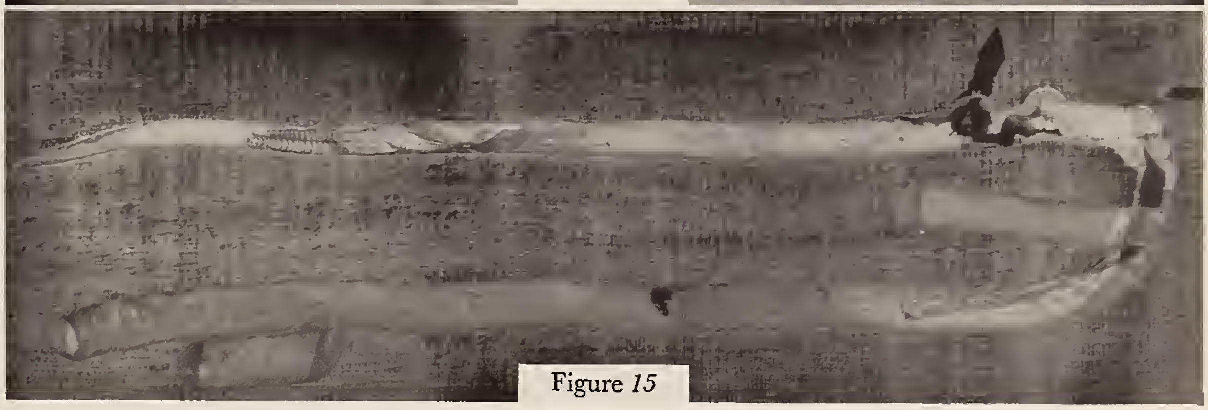

Figure *15*

the same panel made it possible to determine the date each shipworm specimen gained entrance to a panel and made possible observations of growth characteristics of each individual shipworm from month to month. From these specific shipworm growth measurements the magnitude of growth variabilities could be assessed and sometimes the reasons for growth variability could be recognized.

As has been explained earlier, Series II panels were exposed for a 6-month period from 1 January to 1 July 1970. Table 2 summarizes the data obtained from examining the X-ray photographs of this series. The panels were exposed to *Bankia* attack on all surfaces. Most of the settlement occurred between 1 March and 1 April 1970 and the period of observation of growth was for a period of three months from initial detection on 1 April until removal for final X-ray and examination on 1 July. The control panels in each rack (Panels #1 and #2; see Materials and Methods above) were X-rayed only at the end of the exposure period. The duration of growth of shipworms in these panels was assumed to be 3 months as they were probably infested at the same time as Panel #3 in the same rack which was the panel X-rayed monthly. On 1 April one of the deep panels (23 ft. below MLLW) contained 156 *Bankia* having an average length of 24 mm. No additional shipworms were found to have entered this panel in succeeding months, but the 156 specimens increased sufficiently in size that by 1 May the X-rays indicated that the borers were too crowded to make recognition of individuals possible for length measurements. The total surface area of each panel employed in Series II was approximately 1 square foot. Therefore, the total number of *Bankia* per panel was equivalent to settlement per square foot. In general, the number of borers per panel increased with depth in the harbor studies. The floating panels had only a few *Bankia,* while the shallow and mid-water panels had 30–40/sq. ft., and the deep panels contained 84–156/sq. ft.

Length measurements from Series II X-rays were made along the mid-line of the burrow from the point of entrance to the anterior end of the shell. The living shipworms often retracted their shells from the forward ends of the burrows, as may be seen in Figures *6–11*. Therefore, the length measurements recorded in Table 2 are either equal to or less than the actual length of the *Bankia* burrow. The burrow lengths could not be measured directly because of confusion caused by over-crowding (e.g., see Figure 16). The individual shipworm that achieved the greatest length (425 mm) in 3 months of growth was in a deep panel. Due to over-crowding it grew to only 8 mm diameter while a 290 mm *Bankia* in a less crowded panel (Shallow Panel #1) grew to 11 mm diameter. Average growth in the shallow and mid-water panels over the 3-month period ranged between 114 mm and 160 mm. The average monthly growth increment was 43 mm. Numbers and burrow lengths of *Bankia* in the floating panels were minimal partially due to the fact that the racks were occasionally hung up above the water. The mooring mechanism which kept the floating panels just below the water-air interface failed several times and allowed the panels to remain out of water following a period of high tide for up to 36 hours. A greater *Bankia* settlement and growth rate probably would have been recorded had the floating rack's mooring mechanism operated correctly.

The percentage destruction of the wooden panels was approximated by weighing each panel before exposure and comparing it with the weight of the panel after six months of exposure. Panels were air dried and all external fouling growth was removed prior to final weighing, but two factors contributed to minor inaccuracies. Calcium carbonate produced by the shipworms in the form of burrow lining, pallets, and shell added weight to the panel. Surface burrows caused by the gribble *Limnoria quadripunctata* on the ends of some panels decreased the weight. Gribble burrows appear in X-ray photographs as light streaks or as a cobwebbing near the panel ends (e.g., see Figure *18*). The increase in average percent destruction of the wood with increasing depth corresponds very closely to the increase in numbers of *Bankia* per panel. The largest average percent of panel destruction was 28% for the deep panels with almost no destruction occurring in the floating panels of this series.

Two of the three Series II panels at each depth served as controls during this study (see above, Materials and Methods, Series II). Average percentage of destruction for each Panel #1, #2 and #3 at all depths was 17.8%, 12.5% and 16.2% respectively. These values are very similar and indicate no influence on rates of *Bankia* growth relative to short periods of removal from the water and handling or small doses of radiation.

Series III panels were exposed for eighteen months from 1 July 1970 to 1 January 1972. This long term series was made possible by incorporating a modification of the techniques used in Series II. As explained earlier, in order to restrict *Bankia* settlement, Panels #1, #2 and #3 in each Series III rack were wrapped with Seran tape, leaving only the ends with 7 square inches of each panel exposed to the sea water (see Materials and Methods, Series III). In each rack Panel #1 was never removed from water except for brief periods when other panels were being removed and they each retained the original tape envelopes until the terminal X-rays on 1 January 1972. Panels #2, #3 and #4 were removed from the water each month for a similar period of time. Panel #2 in each rack was a control and although removed from the water it was not X-rayed until

## Table 3

Monthly observed lengths (mm) of *Bankia setacea* burrows in Monterey Harbor

| Panel Depth | *Bankia* Specimen Number | 1970 J | 1970 A | 1970 S | 1970 O | 1970 N | 1970 D | 1971 J | 1971 F | 1971 M | 1971 A | 1971 M | 1971 J | 1971 J | 1971 A | 1971 S | 1971 O | 1971 N | 1971 D | 1972 J |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Floating at Surface | 1 | All panels initially exposed 1 July 1970 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 6 | 48 | 116 | 211 | 279 | 363 | 437 | 541 | 672 | 797 |
| Floating 2 ft. below Surface | 1 | | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 8 | 8 | † | | | | | | | | |
| | 2 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 10 | 63 | 114 | † | | | | | | |
| 3 ft. below MLLW (Shallow) | 1 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 7 | 37 | 82 | 139 | 196 | 293 | 372 | 395 | 443 | 503 |
| | 2 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 6 | 50 | 121 | 228 | 300 | 405 | 448 | 493 | 544 | 563 |
| | 3 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 10 | 35 | 85 | 90 | 144 | 199 | 250 | 300 | 379 |
| 13 feet below MLLW (Mid-Water) | 1 | All panels initially exposed 1 July 1970 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 19 | 78 | 171 | 227 | 302 | 338 | 369 | 447 | 490 | 490 | 490 |
| | 2 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 21 | 96 | 158 | 251 | 337 | 395 | 476 | 523 | 552 | 573 |
| | 3 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 14 | 54 | 89 | 136 | 167 | 278 | 369 | 409 | 433 | † |
| | 4 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 12 | 52 | 105 | 143 | 159 | 205 | 294 | 357 | 424 | 503 |
| | 5 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 8 | 83 | 114 | 169 | 211 | 214 | 214 | † |
| | 6 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 7 | 42 | 93 | 218 | 331 | 406 | 420 | 420 |
| | 7 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 8 | 43 | † | | | | | |
| 23 feet below MLLW (Deep) | 1 | | 0 | 0 | 1 | 26 | 82 | 188 | 265 | 324 | → | → | → | 619 | 647 | 647 | † | | | |
| | 2 | | 0 | 0 | 0 | 1 | 29 | 106 | 165 | 228 | 313 | 384 | 456 | 558 | 606 | 655 | 704 | 754 | 802 | 834 |
| | 3 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 14 | 22 | 22 | † | | | | | | |
| | 4 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 10 | 59 | 143 | 268 | 378 | 440 | 440 | 440 | 440 | 440 |
| | 5 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 6 | 53 | 127 | 240 | 285 | → | → | → | → | 465 |
| | 6 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 9 | 27 | 77 | 125 | 244 | 309 | 344 | 344 | † |
| | 7 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 7 | 22 | 61 | 105 | 220 | 302 | → | → | 405 |
| | 8 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 7 | 86 | 144 | 236 | 307 | 369 | 409 | 489 |
| | 9 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 31 | 87 | 193 | 244 | → | → | 413 |
| | 10 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 7 | 70 | 152 | → | 293 |
| | 11 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 32 | 92 |

[2] the dagger symbol (†) indicates shipworm was found dead on the first of the indicated month

## Explanation of Figures *16* to *18*

Figure *16*: X-ray photograph of panel heavily infested with 145 specimens of *Bankia setacea* 3 months following initial detection of the shipworms. Entire panel exposed at a depth of 23 feet below MLLW in Monterey Harbor

Figure *17*: X-ray photograph of Control Panel No. 1 exposed at the location for the same period of time as the panel X-rayed monthly shown in Figure *14*. A second set of pallets is clearly visible.

Figure *18*: X-ray photograph of Control Panel No. 2 exposed at same location for the same period of time as the panel X-rayed monthly shown in Figure *14*

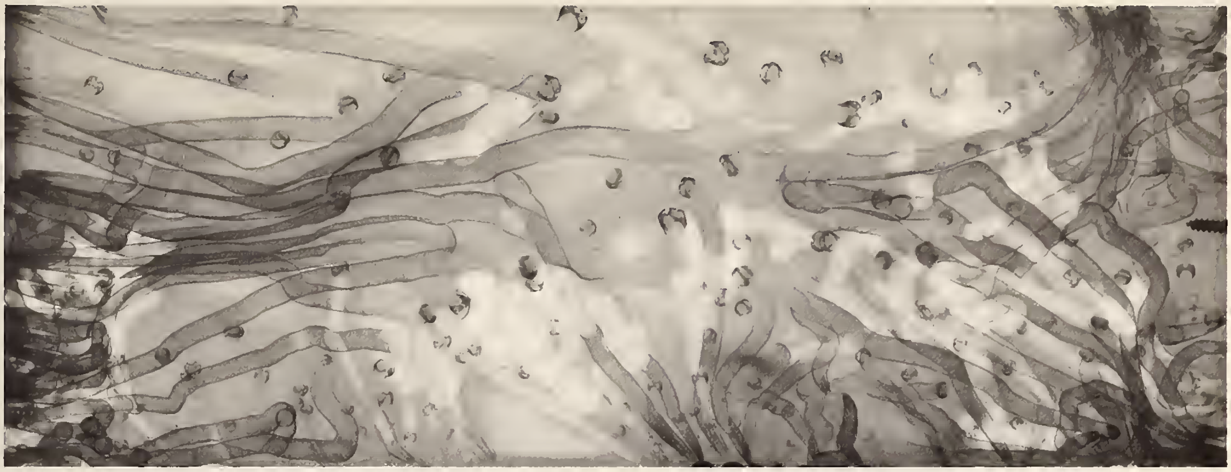

Figure *16*

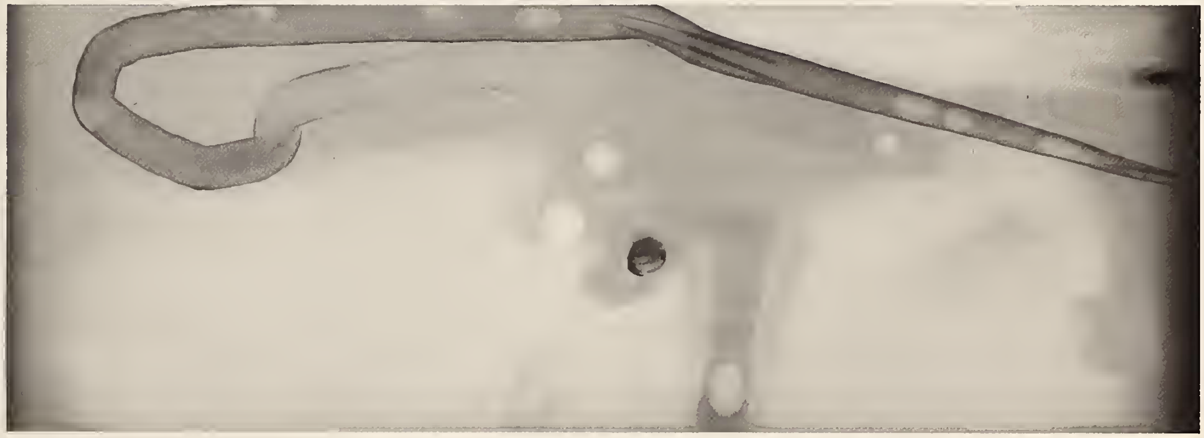

Figure *17*

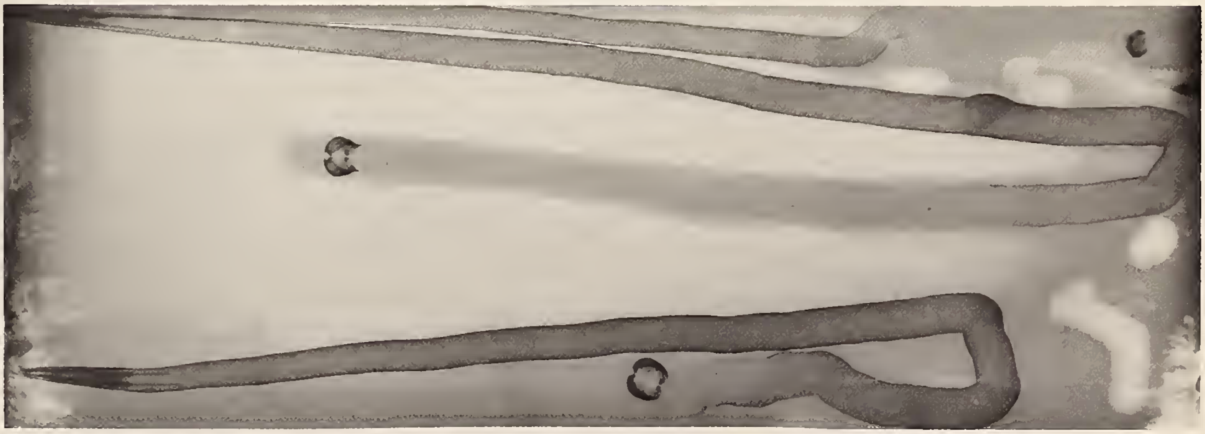

Figure *18*